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Jury, W.A., Stolzy, L.H, Letey, J., Jr., Weeks, L.V. 1974. Evaluation of Critical Soil Properties Needed to Predict Soil Water Flow Under Desert Conditions. U.S. International Biological Program, Desert Biome, Logan, UT. RM 75-40.

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1974 PROGRESS REPORT

EVALUATION OF CRITICAL SOIL PROPERTIES NEEDED TO PREDICT SOIL WATER FLOW UNDER DESERT CONDITIONS

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US/IBP DESERT BIOME
RESEARCH MEMORANDUM 75-40

in

REPORTS OF 1974 PROGRESS
Volume 3: Process Studies
Abiotic Section, pp. 11-15

1974 Proposal No. 2.3.5.2.

Printed 1975

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Citation format: Author(s). 1975. Title.
US/IBP Desert Biome Res. Memo. 75-40.
Utah State Univ., Logan. 5 pp.

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ABSTRACT

The study was devised to develop a predictive model to characterize water movement through desert soils quantitatively in space and time. Previous data from two desert sites on transport coefficients for water movement allowed for the development of a theoretical model to look at heat and water vapor movement under surface rock. Field experiments to test the preliminary model at two desert sites will include long-term monitoring of a natural area, unaltered by irrigation; short-term monitoring of temperature and water content following irrigation representative of area precipitation patterns; short-term monitoring of temperature and water content profiles following an irrigation in which stones are placed after irrigation to determine the effectiveness of stones as evaporative mulch. The preliminary model will be revised when it is compared with field data. At this stage it represents a first attempt to estimate the amount of water moved by heat flow and should, when coupled with a model estimating the movement of liquid water, begin to represent water movement caused by the presence of stones and provide information on the utility of surface rock cover in conservation of moisture in arid climates.

INTRODUCTION

The overall goal of this research study is to develop a predictive model to characterize the movement of water through desert soils quantitatively in space and time. Previous work under this program (Mehuys 1973) has focused on measuring the transport coefficients for water movement of several desert soils at two IBP validation sites (Silverbell, Arizona, and Rock Valley, Nevada).

The study proposed for this year will concentrate on analyzing the effect of surface stones on heat and water movement and on water loss in the desert. A theoretical model for heat and water flow under stones will be applied to measurements of temperature and water content taken under and near surface stones.

OBJECTIVES

By utilizing the information already obtained from previous years, we should be able to roughly characterize the water transport coefficients for the desert sites studied. Research for this year will concentrate on assessing the influence of surface stones on evaporation and water storage through a combination of experimental and theoretical analyses. Specific goals of the study are to:

1. Determine transient soil temperatures at selected locations underneath and adjacent to stones overlying bare soil at field sites in California (UCR) and Arizona (Silverbell Validation Site).
2. Take gravimetric soil water samples under similar stones and adjacent soil to determine, if possible, any transient or cumulative differences in water accumulation.
3. Follow an irrigation (UCR site) with temperature and water content sampling to try to determine the degree to which surface stones aid in storing and conserving infrequent precipitation in an arid climate.
4. Attempt to relate water movement in dry soil to temperature gradients.
5. Compare field measurements to those estimated from a computer-assisted model for two-dimensional heat flow.

THEORETICAL CONSIDERATIONS

Movement of water through a porous medium in the presence of temperature gradients has been studied in the laboratory for many years, but theoretical models proposed to predict the fluxes of water and heat have been only partially successful at explaining the observed values. When the driving variables for flow are taken to be volumetric water content θ and temperature T, the model most frequently employed is that of Philip and de Vries (1957) which describes the fluxes of heat, water vapor and liquid water as

$$\underset{\sim}{q}_{v} = -D\theta_{v}\underset{\sim}{\nabla}\theta - D_{Tv}\underset{\sim}{\nabla}T \qquad (1)$$

$$\underset{\sim}{q}_{l} = D\theta_{l}\underset{\sim}{\nabla}\theta - D_{Tl}\underset{\sim}{\nabla}T - K\underset{\sim}{k} \qquad (2)$$

$$\underset{\sim}{q}_{h} = \rho_{l}L\,D\theta_{v}\underset{\sim}{\nabla}\theta - \lambda\,\underset{\sim}{\nabla}T \qquad (3)$$

where

$\underset{\sim}{q}_{v}$ = flow of water as vapor per area per time ($cm^3 \cdot cm^{-2} \cdot sec^{-1}$)
$\underset{\sim}{q}_{l}$ = flow of water as liquid per area per time ($cm^3 \cdot cm^{-2} \cdot sec^{-1}$)
$\underset{\sim}{q}_{h}$ = flow of heat per area per time ($cal \cdot cm^{-2} \cdot sec^{-1}$)
θ = volumetric water content (cm^3/cm^3)
T = temperature (°C)
L = latent heat of vaporation of water (cal/g)
ρ_{l} = density of liquid water (g/cm^3)
λ = thermal conductivity of moist soil ($cal \cdot cm^{-1} \cdot {}^{\circ}C^{-1} \cdot sec^{-1}$)
$D\theta$ = isothermal moisture diffusivity (cm^2/sec)
D_T = thermal moisture diffusivity (cm^2/sec)
K = hydraulic conductivity (cm/sec)
$\underset{\sim}{\nabla}$ = gradient operator (cm^{-1})
l = liquid
v = vapor
h = heat

In their paper, Philip and de Vries give a procedure for calculating the coefficients $D\theta_l$, $D\theta_v$, D_{Tl}, D_{Tv}, λ, from a knowledge of the soil water characteristic Ψ (θ), capillary conductivity $K(\theta)$ and soil properties (porosity, water content, mineral constituents). However, experimental measurements of the thermal components D_{Tl}, D_{Tv} are scarce, with the existing values of D_{Tl} tending to contradict the predictions of the model (Jury and Miller 1974). Isothermal moisture measurements in dry soil are also lacking, but tend to at least qualitatively confirm the predicted structure (Jackson 1963, Van der Kooi 1971). Thermal conductivity may be calculated to within 10% of measured values by a 1963 model of de Vries (Jury and Miller 1974).

Field tests of equations 1 to 3 are also meager. Rose (1968) used measured temperature and humidity profiles to predict the fluxes according to the model, but had no independent measurements for comparison. Jackson et al. (1974) compared calculated and measured heat and water fluxes in dry soil and found equations 1 to 3 could explain only some of their observations while others were better explained using a model of pure heat conduction and water flow only due to moisture gradients, which is sometimes referred to as the simple theory of heat and water transfer:

$$\underset{\sim}{q}_m = -D\theta \underset{\sim}{\nabla}\theta - K\underset{\sim}{k} \qquad (4)$$

$$\underset{\sim}{q}_h = -\lambda \underset{\sim}{\nabla} T \qquad (5)$$

This field test is by no means conclusive but it does indicate the large gap between theory and measurement in a field situation.

Since a large fraction of the water movement in an arid soil will be in the vapor phase, special attention should be given to the experimental information on temperature-assisted water vapor movement. Letey (1968) summarized a large number of laboratory studies and reported that all of the observed vapor flux measurements could be described well by the equation:

$$J_v = -L_{VQ}(T)\,(dT/dZ) \qquad (6)$$

where $L_{VQ}(T)$ is independent of soil water potential (and hence soil water content) over a large range of suction values. Equation 6 will form the starting point for our investigation of water movement under stones.

Two-dimensional Heat Flow

Because the rocks on the surface form an incomplete cover, it was expected that the heat flow in the soil underneath would move laterally as well as vertically, and a theoretical model was devised to describe two-dimensional heat flow.

For computational purposes, it was assumed that rectangular stones of height H, width W and spacing D were placed periodically over a soil with uniform thermal properties (Fig. 1). At a depth S in the soil the temperature is held constant at a mean value T_0 while the soil and stone surfaces are varied as a function of time. The system of equations to be solved is thus:

$$C_1(\delta T_1/\delta t) = \lambda_1[(\delta^2 T_1/\delta Z^2)+(\delta^2 T_1/\delta X^2)]\ \text{Stone} \qquad (7)$$

$$C_2(\delta T_2/\delta t) = \lambda_2[(\delta^2 T_2/\delta Z^2)+(\delta^2 T_2/\delta X_2)]\ \text{Soil} \qquad (8)$$

$T = f(t)$ soil and stone surfaces
$T = T_0$ at depth $Z = -S$ (9)

Since the arrangement is symmetric, the only segment that needs to be solved is the interval from the middle of a stone to the midpoint between stones, with a boundary condition of zero lateral heat flux through the points of symmetry (Fig. 2).

The system (equations 7 to 9) was solved numerically on the IBM 360/50 computer at Riverside by an alternating direction implicit technique (Douglas and Peaceman 1955) with a space mesh of 1.25 cm and a time step of ½ hr for the case of a sinusoidal temperature at the surface and the following set of system characteristics: S = 25 cm, W = 10 cm, D = 50 cm, H = 10 cm, λ_1 = 234 cal/cm °C day, λ_2 = 58.5 cal/cm °C day, C_1 = .60 cal/cm^3 °C, C_2 = .45 cal/cm^3 °C and $T(t) = 25 + 11\,\text{SIN}\,(2\pi t)$ t in days. Figure 3 shows a set of isotherms for various times of the day.

This simulation shows that the effect of the stones placed on the surface is to create a lateral temperature gradient toward or away from the soil under the stone depending on the time of day. From equation 6 it is reasonable to suppose that this lateral gradient could cause water vapor to move horizontally and affect the normal process of evaporative loss under a radiation demand from the atmosphere.

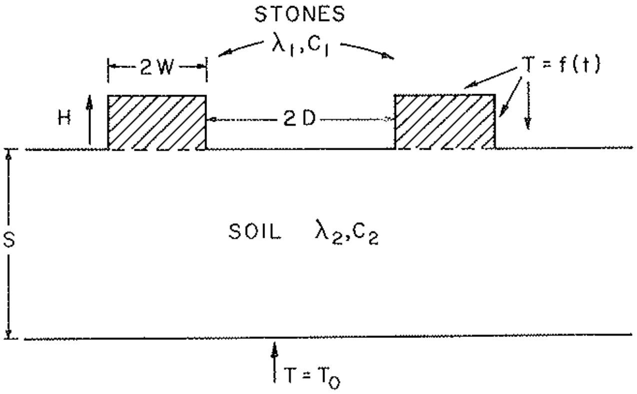

Figure 1. Dimensions of the stone-soil problem.

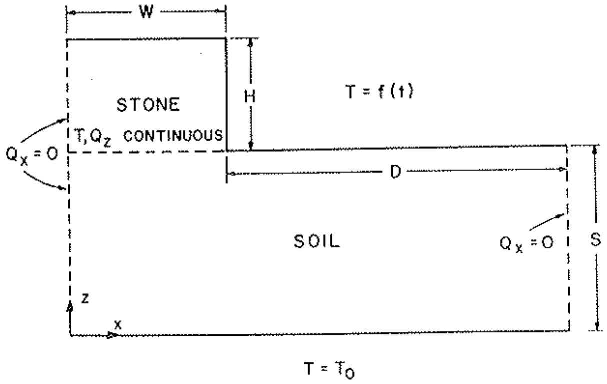

Figure 2. Reduced soil-stone problem with boundary conditions.

To investigate this hypothesis in more detail the following simulation was run. The assumption was made that all water movement took place in the vapor phase according to equation 6 and that the change in water storage within the soil could be described by

$$(\partial \theta / \partial t) + (\partial J_V / \partial Z) = 0 \qquad (10)$$

The heat-flow equations were solved as described above and the resulting temperature profiles fed into equations 6 and 10 to allow moisture profiles to be calculated according to the following boundary conditions:

$$\text{at } Z = -S, \; J_V = L_{VQ}(T)\,(dT/dZ) \qquad (11)$$

under stone:

$$\text{at } Z = 0, \; J_V = 0$$

under bare surface:

$$\text{at } Z = 0, \; J_V = L_{VQ}(T)\,(dT/dZ) \text{ if upward (evaporation)}$$
$$= 0 \text{ if downward}$$

What these conditions correspond to is allowing evaporation to proceed from the bare soil surface providing the heat flux is outward, and not allowing any vapor to enter the soil from the air when the heat flux is into the soil. Figure 4 shows the result of a simulation that assumes an initial water content $\theta = .10$.

This simulation is very crude and unrealistic in its treatment of the evaporative boundary condition. In particular, it should break down when the humidity in the soil drops below saturation. As a first approximation, however, it should indicate the pattern of water circulation due to water movement in the vapor phase. It must be coupled to the liquid phase and to more realistic atmospheric boundary conditions before the predictions can be looked at seriously.

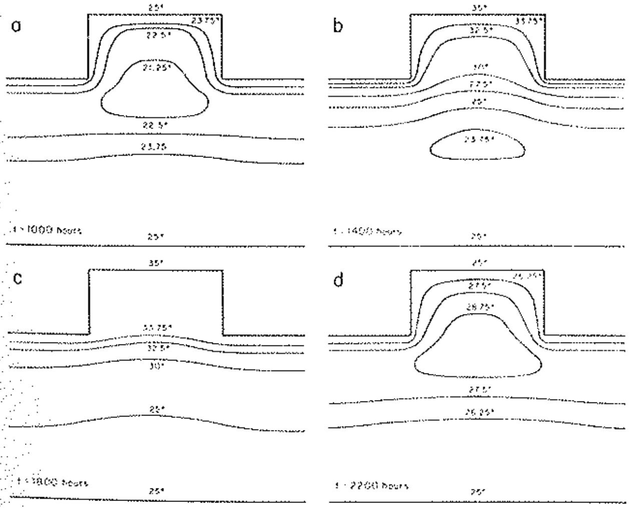

Figure 3. Simulated isotherms for four times of day in soil-stone problem.

EXPERIMENTAL METHODS

In order to test out the above ideas, several field experiments have been devised to measure the temperature distribution under stones and to determine differences in water accumulation under rocks and under bare soil.

The first site is a level, bare field in the botanical gardens at the University of California at Riverside. A number of large flat stones have been placed on the surface at various locations around the field. One rock overlies a soil section that has been instrumented with 12 copper-constantan thermocouples located as shown in Figure 5 and monitored by a Leeds and Northrup Speedomax H recorder coupled to an electronic reference junction. Temperature profiles will be taken continuously during a field run and will be supplemental with periodic gravimetric sampling of the surrounding soil and adjacent rocks to attempt to determine differences in water storage patterns. Three kinds of field tests are planned: 1) a long-term monitoring of the field in a natural state unaltered by irrigation; 2) a short-term intensive temperature and water-content monitoring of the field following an irrigation representative of precipitation patterns for the area; 3) a short-term intensive monitoring of

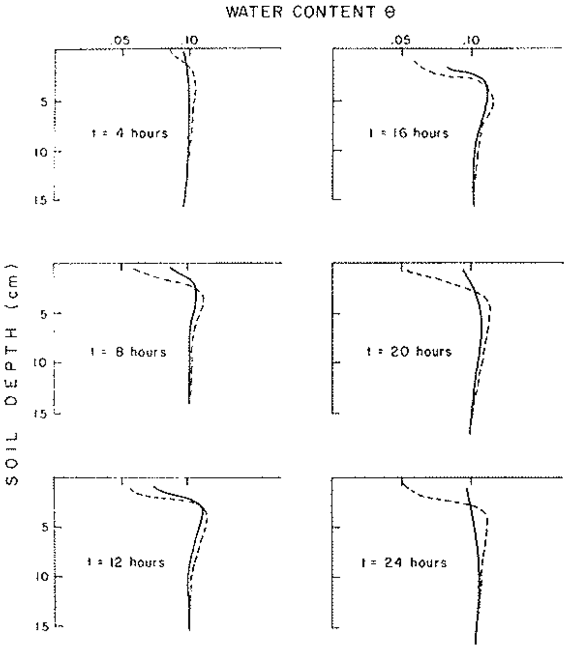

Figure 4. Simulated water content profiles in soil-stone problem.

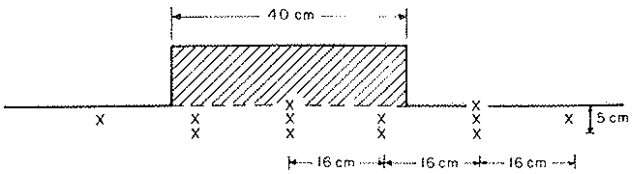

Figure 5. Thermocouple locations in field experiment.

temperature and water-content profiles following an irrigation in which the stones were applied after the water, to determine how effective the stones are as an evaporative mulch.

Concurrent with the field experiments at Riverside will be a similar set of temperature measurements under rocks set up at the IBP validation site at Silverbell, Arizona. It is hoped that, by monitoring several stones of different properties, we can gain further information on the effect of the cover on heat flow in soil.

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